The EMG activity and mechanics of the running jump as a function of takeoff angle

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Abstract

To characterize the electromyographic (EMG) activity, ground reaction forces, and kinematics were used in the running jump with different takeoff angles. Two male long jumpers volunteered to perform running jumps at different approach speeds by varying the number of steps (from 3 to 9) in the run-up. Subject TM achieved a greater vertical velocity of the center of gravity (CG) at takeoff for all approach distances. This jumping strategy was associated with greater backward trunk lean at touchdown and takeoff, a lesser range of motion for the thigh during the support phase, more extended knee and ankle angles at touchdown, and a more flexed knee angle at takeoff. Accompanying these differences in kinematics, TM experienced greater braking impulses and lesser propulsion impulses for the forward–backward component of the ground reaction force. Furthermore, TM activated mainly the rectus femoris, vastus medialis, lateral gastrocnemius, and tibialis anterior, while if rarely activated the biceps femoris from just before contact to roughly the first two-thirds of the support phase. These results indicate that TM used a greater takeoff angle in the running jump because he enabled and sustained a greater blocking effect via the coordination patterns of the muscles relative to the hip, knee, and ankle joints. These findings also suggest that the muscle activities recorded in the present experiment are reflected in kinematics and kinetics. Further, the possible influence of these muscle activities on joint movements in the takeoff leg, and their effect on the vertical and/or horizontal velocity of the jump are discussed. © 2001 Elsevier Science Ltd. All rights reserved.

Keywords: EMG activity; Kinematics; Kinetics; Jumping style; Coordination

1. Introduction

The generation of vertical velocity to obtain vertical lift while maintaining horizontal velocity is a critical element in long jumps for maximum distance. For example, Hay and colleagues [8,9,13] have described selected characteristics of the techniques used by elite long jumpers during the transition from approach to takeoff in the long jump and identified the characteristics that were significantly related to the distance of the jump. Koh and Hay [13], for example, found that the distance of the jump correlated with touchdown distance ($r = 0.44$) and the change in horizontal velocity ($r = -0.59$). They suggested that placing the landing foot well forward of the body at the end of the last stride promotes the development of vertical velocity at the expense of the loss in horizontal velocity during the support phase of the jump. Similarly, Lees et al. [15,16] concluded that a fast run-up and lowered center of gravity (CG) help to place the leg well in front of the body, which permits the CG to ride up over the base of support and enables the takeoff leg to store elastic energy that can contribute to the change in vertical velocity.

However, the strategies used in such tasks can vary among individuals. For example, the styles of Mike Powell (distance =8.95 m) and Carl Lewis (distance =8.91 m) at the Third World Championships in 1991 were quite different. Fukashiro et al. [3] reported that Powell achieved a greater vertical velocity and takeoff angle (23.1° =0.40 rad) due to inclination of the trunk, a more extended support leg, and larger hip rotation. In contrast, Lewis preserved horizontal velocity by limiting extension of the support leg, which resulted in a lower takeoff angle (18.3° =0.32 rad). Because these two individuals jumped a similar distance with different takeoff
angles, we were interested in the biomechanical details of the takeoff associated with various takeoff angles. Previously, we captured the relationship existing between movement output (i.e. the kinematics and ground reaction forces) and movement process leading to this output (i.e. electromyographic (EMG) activity) by an analysis of the running jump executed with various takeoff angles using a short approach distance [12]. For example, subjects achieved a greater vertical and lesser horizontal velocities due to lesser EMG activation of the biceps femoris muscle, limiting extension of the thigh, and greater braking force. In contrast, subjects maintained horizontal velocity by activating the lateral gastrocnemius and soleus muscle and experiencing greater propulsive force, which resulted in a lower takeoff angle. In this study, we found that there were distinctly different jumping strategies that varied from nearly horizontal to nearly vertical trajectories and how they affected the takeoff velocities.

The purpose of the study was to characterize the EMG activity, ground reaction forces, and kinematics used in the running jump with different takeoff angles. We examined the strategies used by two long jumpers skilled in the running jump, but who used different takeoff angles. The present study was designed to examine this behavior in greater detail by varying the approach speed with progressively increasing approach distances. The description includes the measurement of EMG activity, which has not been compared previously for these two jumping styles [3].

2. Methods

After informed consent was obtained, two male long jumpers (TM: 175 cm, 67 kg and YS: 177 cm, 67 kg) participated in the study. After a warm-up, they were instructed to perform a takeoff technique as in a competition and performed running jumps at different approach distances chosen to explore the regularities in the run-up. This short and a progressively increasing approach distance was intended to examine the strategies used by two long jumpers skilled in the running jump with different takeoff angles. We performed 2–4 times at each step approach in an indoor hall with a rubber mat placed along the runway and over the force platform (Type 9281B, Kistler). Because the jumps were performed indoors, the subjects landed on a mat instead of sand. The longest distance ever jumped by TM (a 200 m participant at the Atlanta Olympic Games) was 7.63 m and that for YS was 6.80 m. The distances jumped in these experiments were measured from the toe of the takeoff leg to the heel of the contralateral leg at touchdown.

2.1. Kinematic and ground reaction force measurements

The vertical ($F_z$), forward–backward ($F_x$), and side-to-side ($F_y$) components of the ground reaction force and the location of the center of pressure were measured using a force platform. The analog signals were amplified, digitized at 1000 Hz, and stored on a personal computer.

To assist in determining the kinematics of the motion, several anatomical landmarks were identified with 2 cm markers: ankle; knee; hip; wrist; elbow; shoulder; top of the head; center of the ear; center of the neck; tip of the little finger; and fifth metatarsal joint [18]. Subjects were videotaped in the sagittal plane with a high-speed camera (HSV-500, NAC, Tokyo) set to operate at 250 frames/s. The camera was positioned on a tripod that was located 1.1 m above the ground and 11 m from the runway. The signal of $F_z$ component of the ground reaction force was also recorded on the videotape so that the kinematic and temporal data from the force platform could be synchronized. The duration of each trial included 20 frames before touchdown to 20 frames after takeoff.

The coordinates of the anatomical landmarks were extracted from each frame by a motion analyzer (SPORTIAS, NAC, Tokyo) for the calculation of joint angles and the determination of CG location. The knee and ankle joints were defined as the inclusive angles between the adjacent body segments. Trunk angle was defined relative to the forward horizontal while thigh angle was defined relative to the backward horizontal. After appropriate scaling, the absolute coordinates were low-pass filtered (second-order Butterworth) at 12 Hz for segment data and 8 Hz for CG location. The position of the CG for the whole body was determined from those for the 15 body segments according to the method of Miura et al. [18], which is modified for Japanese body dimensions. The velocity of the CG was computed along the jumper’s path of motion in the horizontal ($x$) and vertical ($y$) directions. Angular velocities were determined by numerical differentiation. The takeoff angle was calculated as the mean angle of projection of the CG during the five consecutive film frames after the takeoff. The touchdown distance was the horizontal distance between CG and the toe of the support foot.

2.2. EMG activity measurements

The EMG activities were recorded from the following muscles of the takeoff leg: the long head of biceps femoris (BF); vastus medialis (VM); rectus femoris (RF); lateral gastrocnemius (LG); tibialis anterior (TA); and soleus (Sol). Disposable electrodes (Vitrode S, Nihonkoden, Tokyo; Ag–AgCl electrodes) were placed on the belly of the investigated muscles, longitudinally to the muscle fibres, with a 3 cm center-to-center distance. The
ground electrode was placed over the tibia. The skin was shaved and prepared with fine sandpaper and ethanol to lower the skin impedance and favor proper recordings of the muscle potentials. To minimize myoelectric contributions from close synergistic muscle, the electrodes were placed centrally over the muscle belly. To minimize artifacts, the electrodes on the skin and the cables from electrodes to the telemetric pre-amplifiers were fixed to the body surface to make them stable using surgical and under wrap tapes. The EMG transmitter was also fixed with a belt around the waist of the subjects.

All EMG signals were amplified and transmitted telemetrically (WEB-5000, Nihonkoden, Tokyo; impedance 10 MΩ; signal-to-noise ratio >54 dB), and the lower and upper cut-off frequencies were 15 and 250 Hz, respectively. The $F_z$ component of the ground reaction force and EMG signals were also monitored on a thermal array recorder (RTA-1200, Nihonkoden, Tokyo) and recorded, for later analysis, on magnetic tape by an FM-14 channel recorder (XR-510, TEAC, Tokyo; bandwidth DC-2500 Hz). The tapes were played back, and the EMG signals were then full-wave rectified and smoothed (EI-601G, Nihonkoden, Tokyo; time constant 10 ms), and digitized at 1000 Hz frequency using a 12 bits A/D converter.

It was necessary in our study to examine kinematic, kinetic, and EMG variables during takeoff simultaneously. A trial was considered for analysis if: (a) subjects performed a takeoff technique as similar as possible to that; (b) touchdown was made naturally inside of the force platform; and (c) possible moving artifacts was minimal. The trials that met these criteria were analyzed.

### 3. Results

The different jumping strategies of the two subjects were evident by comparing the CG velocity at touchdown and at takeoff. For both subjects, the horizontal velocity of the CG at touchdown and at takeoff increased with the number of steps used in the approach (Table 1). Similarly, vertical velocity at takeoff increased with the number of steps for Subject TM, but not consistently for Subject YS. Perhaps the most significant difference between the two jumpers was that horizontal velocity was less at takeoff than at touchdown for TM whereas it was greater at takeoff for YS (Fig. 1). Consistent with this difference, the vertical velocity at takeoff was greater for TM, and hence he had greater takeoff angles for all three approach distances compared with YS (Table 1).

These differences in CG velocities were accompanied by differences in limb kinematics and in the ground reaction forces. For both subjects, the thigh rotated backward for the duration of the stance phase with little difference in the range of motion for the different approach distances (Fig. 2a and b). However, the range of motion was greater for YS. Nonetheless, peak angular velocity for the thigh increased modestly across the three approach distances for both the subjects (Fig. 2c and d). The greatest difference between the two subjects in terms of leg kinematics occurred at the knee joint. At touchdown, knee angle was more flexed for YS compared with TM (Table 1) and displacement about the knee joint during the support phase was more symmetrical for TM with greater angular velocity than YS in the direction of knee flexion (Fig. 2). However, for both subjects there were no systematic changes in knee joint kinematics across approach distances. At takeoff, the knee joint was more extended for YS (Table 1). Displacement about the ankle joint was more similar between the two subjects, although the ankle was more flexed at touchdown for YS (Table 1) and TM varied the displacement across the three approach distances (Fig. 2).

The duration of the support phase (touchdown to takeoff) decreased with an increase in the number of steps in the approach for both subjects (Fig. 3). Accordingly, the average magnitude of the vertical component ($F_z$) of the ground reaction force increased as a function of approach distance. The shape of the $F_z$–time record was similar across conditions for TM, with the addition of a large impact peak for the 9-step approach (Fig. 3a), which increased the $F_z$ impulse (Fig. 3c). Subject YS

<table>
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The changes in selected kinematic variables from touchdown to takeoff as a function of the number of steps in the approach (3, 5, or 9) for the two subjects.
Fig. 1. Horizontal and vertical velocity of the center of gravity (CG) for subjects TM and YS at touchdown and takeoff of the support phase for the running jump. The data are for the 3-, 5-, and 9-step approaches (SA). a and c: stick diagrams at 40-ms intervals. The CG is indicated by ▲. b and d: Horizontal and vertical velocities at touchdown (● and ▲) and takeoff (○ and △). θ indicates the takeoff angle.

Fig. 2. Angular displacements and velocities for the thigh, knee, and ankle angles of subjects TM and YS across the three approach distances. The angles are defined on the stick figures to the right. The data for the 3-step approach (SA) are indicated with a dotted line, the 5-step approach with a dashed line, and the 9-step approach with a solid line. The support phase is the duration from touchdown (TD) to takeoff (TO).
tended to scale the $F_z$-time records across conditions with systematic decrease in support duration and increase in the magnitude of the impact force (Fig. 3d). The most pronounced difference in the ground reaction force between the two subjects was in the forward–backward ($F_y$) component. Subject TM had larger braking impulses and smaller propulsion impulses for all the three approach distances compared with YS (Fig. 3e and f). This would explain the increased vertical velocity of the CG for TM during the support phase.

Because of differences in CG horizontal and vertical velocities, leg kinematics, and the ground reaction forces between the two subjects, some of EMG patterns appeared to be different between the two subjects (Fig. 4). General characteristics of the EMG activity tended to show rather longer duration phase, and the initiation of the EMG activity started progressively earlier in the touchdown as the approach speed increased for TM. However, little change was observed in the timing of initiation in the EMG for YS as the approach speed increased. A typical double burst EMG of rectus femoris muscle could be observed. The first burst was followed by a silent period and then by a burst during support phase. The second burst at support phase of rectus femoris muscle for TM showed phase shifted forward in time to start at touchdown as the approach speed increased. The marked increase in the vastus medialis EMG activity for TM prior to ground contact are shown at 9-step approach. It is interesting that the pattern of biceps femoris EMG activity was markedly different between the two subjects. A burst EMG activation of the bicep femoris muscle for YS was observed from just before touchdown to the first half of the support phase and was followed by a silent period. In contrast, a less distinctive observation was seen in the bicep femoris EMG burst activity for TM during the same phase. The tibialis anterior EMG activity for TM increased tonically before the touchdown and greater activation occurred during support phase as the approach speed increased, combined with considerable co-activation of the lateral gastrocnemius EMG activity. However, the EMG activity for YS appeared reciprocally in time with the lateral gastrocnemius EMG activity at the instant of the foot contact. The soleus muscle showed no remarkable
increase during the support phase as the approach speed increased for both subjects.

4. Discussion

The study examined the biomechanical factors that distinguished jumping style between the two long jumpers. TM achieved a greater vertical velocity of the CG at takeoff compared with YS. This jumping strategy was associated with greater backward trunk lean at touchdown and takeoff, a lesser range of motion for the thigh during the support phase, more extended knee and ankle angles at touchdown, and a more flexed knee angle at takeoff. Accompanying these differences in kinematics, TM experienced greater braking impulses and lesser propulsion impulses for the forward–backward component of the ground reaction force. Furthermore, the burst EMG activation of the rectus femoris and vastus medialis for TM occurred from just before contact to roughly the first two-thirds of the support phase. In contrast, the biceps femoris EMG activity was moderate. The EMG activities for tibialis anterior and lateral gastrocnemius exhibited co-activation from just before contact to roughly the first two-thirds of the support phase as the approach speed increased. However, the reciprocal activation of the tibialis anterior and lateral gastrocnemius occurred at the instant of the foot contact for YS.

In a long jump takeoff, the trunk had the largest backward inclination with a more extended takeoff leg at touchdown, and this significantly affected the distance of the long jump [7]. Furthermore, Koh and Hay [13] reported that placing the takeoff foot far enough ahead of the body at touchdown benefits the distance of the jump, by promoting the development of vertical velocity during the support phase of the long jump. This finding is supported by the data of Hay et al. [10] and Lees et al. [15,16]. In addition, Lees et al. [15] stated that this leg action will lead to a greater braking horizontal force and a consequent loss of horizontal velocity. Similarly, Kyrolaainen et al. [14] found a larger knee angle at touchdown, and greater braking and lesser propulsion ground reaction force during the takeoff in the successful long jumper. These findings were also in accordance with our results. Thus, it is assumed that the differences in CG horizontal and vertical velocities between the two subjects were accompanied by differences in the limb kinematics and in the ground reaction forces.

There have been few reports in the literature on EMG activity at the takeoff of running jump, compared with the literature on limb kinematics and ground reaction force. Perhaps, the most interesting finding in our study was the EMG pattern of the takeoff leg, which differed between the two subjects. This difference altered the control of the takeoff leg, which was reflected in the differences of the $F_x$ and $F_y$ components of the ground reaction force and measures of jump outcome, namely takeoff velocity. For TM, the biarticular rectus femoris (hip flexor and knee extensor) showed increased intensity and duration of activation from just before touchdown to the first half of the support phase and overlapped the monoarticular vastus medialis (knee extensor) as the approach speed. However, for YS such an EMG pattern was not observed. The EMG pattern for TM probably occurred because TM planted his takeoff foot
with a more extended knee angle and backward inclination of the body at touchdown as the approach speed increased. Hashimoto et al. [6] showed that when a subject walked with a backward trunk lean, medial hamstrings reduced their activity while rectus femoris was sustained, the knee was more extended at touchdown, and ground reaction force lines passed near the hip joint during the support phase. This strategy suggests that the knee extension force was predominantly required to support the body load. In previous studies [1,6,20], it has been hypothesized that the rectus femoris muscle and the vastus medialis muscle interact as mutual synergists during this phase, so it seems that rectus femoris muscle for TM contributed to act as knee extensor more so than it did for YS, thus to brake knee flexion against body load. It is possible that such a muscle activity for TM lead to the generation of a greater vertical velocity at takeoff [15,16].

Marked differences were found in the EMG pattern of the biceps femoris across approach distances for both subjects. A burst of EMG activation of the biceps femoris muscle for YS could be observed from just before touchdown to the first half of the support phase and was followed by a silent period. In contrast, a less distinctive observation was seen in the biceps femoris EMG burst activity for TM during the same phase. In the latter case, the burst was followed by EMG activity of longer duration. Since the biceps femoris is a biarticular muscle, the larger EMG burst from just before touchdown to the first half of the support phase for YS may correspond with active hip extension. This biceps femoris EMG pattern for YS is also seen in the same phase of walking [6] and sprinting dash [11], when the trunk leaned forward. Jacobs and Ingen Schenau [11], for example, observed that mainly the activation in the biceps femoris contributed to act as a hip extensor just before touchdown, resulting in a relatively small braking force at touchdown. Some findings by Jacobs and Ingen Schenau are in accordance with our results about the differences of jumping style between the two long jumpers.

Furthermore, the EMG patterns of agonist and antagonist muscles relative to the ankle joint also different between the two subjects and thus the control of the ankle joint (Figs. 2 and 4). For TM, the magnitudes of EMG activity for lateral gastrocnemius from just before contact to roughly the first two-thirds of the support phase were gradually increased as the approach distance increased, with considerable co-activation with the tibialis anterior. Co-activation between tibialis anterior and lateral gastrocnemius could be observed, suggesting an increase of the stiffness and hence stability of the ankle joint [2,19]. This allows the knee and ankle joint to resist the early impact force [4,5,17]. Kyröläinen et al. [14] suggested that high muscle stiffness could be considered as characteristic of a successful takeoff in the long jump. For YS, however, the EMG activity for YS appeared reciprocally in time with the lateral gastrocnemius EMG activity at the instant of foot contact. Touchdown with the heel first and the following plantar flexion occurred.

In summary, the biomechanical factors that distinguished jumping style between two long jumpers are as follows: in kinematics, TM achieved a greater vertical velocity of the CG at takeoff for all approach distances compared with YS. This jumping strategy was associated with greater backward trunk lean at touchdown and takeoff, a lesser range of motion for the thigh during the support phase, more extended knee and ankle angles at touchdown, and a more flexed knee angle at takeoff. In kinetics, TM experienced greater braking impulses and lesser propulsion impulses for the forward–backward component of the ground reaction force. In EMG activity, for TM considerable overlapping of the rectus femoris, vastus medialis, lateral gastrocnemius, and tibialis anterior EMG bursts and a less distinctive biceps femoris EMG burst could be seen from just before contact to roughly the first two-thirds of the support phase. These findings indicate that TM used a greater takeoff angle in the running jump because he enabled and sustained a greater blocking effect via the coordination patterns of the muscles relative to the hip, knee, and ankle joints.

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References


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